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Speeding Up Cable Pipes With Advanced TDMA

Extending the DOCSIS specification can yield higher performance on the return path of cable modems

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The DOCSIS 1.0 and 1.1 specifications define the physical-layer RF interfaces for data-over-cable systems.[1]

With the success of DOCSIS-based broadband access to homes and businesses, the demand for greater symmetric capacity is growing rapidly. This articlediscusses the physical layer (PHY) enhancements developed to increase the effectiveness of transmission in the upstream or return-path direction, in which cable modems send data in time-division multiple access (TDMA) mode to the cable modem termination system (CMTS) at the headend. The future DOCSIS 2.0 specification will include both advanced TDMA and synchronous code division multiple access (S-CDMA) modes.

The key parameters of advanced TDMA are summarized in **Table 1** [2] advanced TDMA is designed to operate with the worst-case impairments reported in cable plants. [3,4] Typical impairments and applicable mitigation techniques are as follows:

- AWGN: mitigate with FEC and by minimizing implementation loss.
- **Impulse/burst noise:** handle with FEC and interleaving.

- **Narrowband ingress:** use ingress cancellation and frequency avoidance.
- **Common path distortion:** treat in same manner as ingress.[5]
- **Micro-reflections:** combat with transmit equalization.
- **Hum modulation:** use properly designed receiver tracking loops.

TABLE 1: Key Parameters of Advanced TDMA PHY

Category	DOCSIS 1.0/1.1	Advanced TDMA
Modulation	QPSK, 16-QAM	QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM
Symbol rates (Mbaud)	0.16, 0.32, 0.64, 1.28, 2.56	0.16, 0.32, 0.64, 1.28, 2.56, 5.12
Bit rates (Mbps)	0.32 - 10.24	0.32 - 30.72
FEC	Reed-Solomon, T = 0 to 10	Reed-Solomon, T = 0 to 16
Interleaving	None	RS byte; block length may be adjusted dynamically to equalize interleaving depths Equalization
Transmit equalizer with	Transmit equalizer with 24 T-spaced taps	8 T-spaced taps
Ingress mitigation	Vendor specific	Receiver ingress cancellation
Preamble	QPSK or 16-QAM;	QPSK-0 (normal power) and QPSK-1 (high length * 1,024 b power); length * 1,536 b (* 768 T)
Spurious emissions	Sufficient for 16-QAM	Generally 6 dB tighter to support 64-QAM

Trade-offs leading to advanced TDMA

Three technologies have been considered for advanced upstream transmission: advanced TDMA, S-CDMA, and orthogonal frequency division multiplex (OFDM). [6] For each technology, the access method during initial registration and station maintenance is TDMA. In addition, in each of the considered technologies time slots are assigned to different users, so all three schemes include TDMA burst transmission and TDMA medium access control (MAC). Thus, all three schemes require a TDMA burst modem, with varying synchronization requirements. S-CDMA and OFDM can be viewed as

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extensions of TDMA transmission to two-dimensional (2D) framing: time/code in the case of S-CDMA, and time/tone in the case of OFDM.

Impulse noise sensitivity: With 2D schemes, multiple codes or tones are transmitted simultaneously; hence, individual symbols are lengthened in time by a factor of the number of codes or tones. The longer symbol duration provides an advantage in the presence of weak impulse noise, because the impulse energy is spread among the concurrently transmitted symbols.

However, this advantage turns into a disadvantage if the impulse energy exceeds a certain threshold; then more symbols are affected in these schemes than in pure TDMA.

Coding and interleaving can help here: If the corrupted symbols can be grouped such that each code word contains a small number of errors, the decoder can correct the noise burst.

Narrowband ingress sensitivity: With TDMA, agility in modulation bandwidth and carrier frequency can be used to avoid RF bands with known severe interference. Remaining narrowband interference can be mitigated by adaptive ingress cancellation. With S-CDMA, cancellation techniques can, in principle, be employed at the chip rate. However, the large decision delay due to the inherent chip-to-symbol conversion process prevents instant availability of reliable decisions. Other estimation and subtraction techniques of much greater complexity must be employed.

To cope with dynamically occurring narrowband ingress, S-CDMA can use spreading as a form of signal repetition, trading bandwidth efficiency for robustness against narrowband noise. For example, spreading by a factor of 10 leads to a 10-dB processing gain at the expense of a 90% loss of capacity, an unattractive trade-off.

In an OFDM system, narrowband interference can be avoided by not using the affected tones. Frequent tone reassignment is then required for both cable modems and the CMTS to avoid dynamic ingress noise, making the protocol complicated and less efficient. OFDM is also more sensitive to unrecognized low-level narrowband interference than TDMA.

Synchronization sensitivity: 2D schemes can require much tighter synchronization to maintain orthogonality between codes or tones. For S-CDMA, the timing accuracy requirement for uncoded 64-QAM is plus/minus 3 ns, while it is plus/minus 250 ns for TDMA, if timing is re-acquired on each burst.

For S-CDMA, the timestamp scheme currently used to control DOCSIS TDMA slot timing has to be replaced with a higher accuracy approach that locks the modem to the downstream symbol clock, with

fine-grain (0.4 ns) timing adjustments sent periodically from the headend. S-CDMA is also sensitive to amplitude and phase fluctuations across the band due to imperfect equalization and ingress cancellation. The result can be a self-inflicted noise floor due to inter-code interference. OFDM uses a cyclic prefix between blocks, making it less sensitive to timing offsets than S-CDMA. However, OFDM is much more sensitive to carrier phase noise and frequency offset than TDMA.

MAC Impacts Of 2D Schemes

Complexity and compatibility with the MAC and transmission convergence (TC) layers of DOCSIS 1.0/1.1 are issues for the integration of a 2D scheme.

Bandwidth allocation is more complex since the scheduler must be able to schedule in time for DOCSIS 1.0/1.1 modems and time/code or time/tone for advanced PHY mo-dems. This requires a change to the MAC/PHY interfaces and tight coupling between the MAC and PHY; otherwise, there may be unused codes/tones, causing capacity loss.

Since 2D schemes require block-based processing based on frames, the latency is increased, which can pose a problem for delay-sensitive applications such as voice over IP (VoIP). Some versions of OFDM utilize dynamic bit loading per tone, requiring modifications to the fixed mini-slot format such as constant bytes per time interval in the DOCSIS MAC. An important element of advanced TDMA is its tighter specifications on spurious emissions. To a first approximation, with 64-QAM operation on the plant, cable modems must provide 6 dB higher suppression of out-of-band emissions than with DOCSIS 1.0/1.1, which uses 16-QAM transmission at most. Otherwise, self-noise could limit system performance. The spurious emissions requirements were tailored to the performance achievable with practical low-cost power amplifiers.

Similarly, carrier phase noise and transmitter modulation error ratio (MER) were tightened to preserve performance for 64-QAM, while weighing implementation complexity and the availability of low-cost oscillators.

Burst Receiver Implementation

Figure 1 shows a typical burst receiver. The receive equalizer may include an adaptive ingress canceller. The analog front-end may include a high-sampling-rate analog-to-digital converter (ADC), which allows direct digital sampling of the entire upstream band (5 to 42 or 5 to 65 MHz). Channel-quality monitoring capability utilizing an fast Fourier transform (FFT) can be integrated into the receiver to support spectrum management and provide the ability to detect, characterize, and avoid interference.[5]

Figure 2 shows measured performance of an advanced TDMA burst receiver in AWGN with 64-QAM modulation and short packets RS (99,73). The theoretical curve for an ideal continuous receiver with RS (99,73) forward error correction (FEC) is shown for reference. The performance reflects the use of modern digital receiver design techniques and a high level of VLSI integration.

Figure 3 displays measured samples of a 64-QAM advanced TDMA signal with four narrowband interferers. The receiver ingress canceller was able to remove the interference and provide quasi-error-free performance.

The advanced TDMA PHY adds interleaving as an important mitigation feature against burst noise, used in combination with FEC. DOCSIS contains a great deal of flexibility in burst parameters such as modulation, preamble, and FEC, which permit a trade-off of receiver processing complexity vs. robustness. In this section we consider only interleaving and FEC, since they are defined by the transmission waveform and provide a performance bound.

Burst noise is characterized statistically by its level, duration, and inter-arrival time.4 Some sources of burst noise are quasi-periodic; for example, AC-line-based noise. Performance is often specified and measured in practice using a periodic burst noise model.5 The burst noise level can reach C/I = -10 dB in the signal bandwidth. The duration is normally 1 microseconds or less, with infrequent isolated occurrences up to 50 microseconds, and average inter-arrival time of about 10 ms (100-Hz repetition rate). System performance is measured by the packet error rate (PER) vs. FEC code rate (kn in the RS codewords). To characterize performance in the presence of burst noise, we ignore fragmentation and concatenation and settle on two payload sizes: 74 B (for a typical short packet) and 1,528 B (for a long Ethernet packet).

Figure 4 shows the performance of advanced TDMA interleaving/ FEC in the presence of burst noise for Reed Solomon T = 16. The analysis assumes the corruption of all symbols coincident with the noise burst plus an additional symbol before and after the noise burst. Points A and F use no interleaving, while points B and G use two interleaved RS codewords; points C and H, four codewords; points D and I, 32 codewords; and points E and J use the maximum interleaver depth of 64 codewords.

Each point in **Figure 4** is a bound on the burst noise duration and repetition rate that can be corrected by the selected settings for the interleaver, FEC, and modulation.

Conservatively, any duration and repetition rate of burst noise less than these values can be corrected. This results in a rectangular region to the left and below each point. Case E is selected as an example in the figure. The region of typical burst noise that occurs in real cable plants

is also depicted at the lower left; considerable margin is available in most cases. Actual performance, including acquisition effects, will approach these bounds but should lie below them.

The described enhancements to the PHY for upstream transmission provide increased capacity in the return path of data-over-cable systems. The approach is to extend the successful DOCSIS system in an evolutionary manner for both higher throughput and increased robustness. Attention is important to backward compatibility with 1.0/1.1 modems, coexistence between advanced TDMA and legacy modems, and specifications to permit interoperability between multiple vendors who will implement the enhanced waveform.

Advanced TDMA modems employ digital techniques to mitigate worst-case plant impairments. This permits the use of portions of the upstream band that were previously unavailable due to strong impulse noise or narrowband ingress. The result is expanded capacity of data-over-cable systems in support of new broadband services demanding higher symmetrical throughput, including voice, video telephony, video conferencing, and distributed servers.

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